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# THE MAGNETIC FIELD IN SUPERCONDUCTING SHIELDED SYNCHRONOUS MACHINES

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Foreign Technology Division
Wright-Patterson Air Force Base, Ohio

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# FOREIGN TECHNOLOGY DIVISION

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# THE MAGNETIC FIELD IN SUPERCONDUCTING SHIELDED SYNCHRONOUS MACHINES

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(Moscow)

The magnetic field of the superconducting winding of a shielded synchronous machine is investigated, expressions for components of magnetic field strength are obtained, and the shape factor of the field of a synchronous machine with ferromagnetic and superconducting shields is determined.

Graphic dependences are given for the distribution of the components of magnetic field strength along the radius for various numbers of pairs of poles, and the relationship of geometrical dimensions of a superconducting winding and shield is shown.

In work [1] a superconducting synchronous machine without ferromagnetic parts was discussed. In such a construction of a superconducting synchronous machine the external magnetic fields reach great values, which can have a negative influence on the working of certain electrotechnical equipment situated near the machine. In connection with this the problem arises of shielding the magnetic field of the working area of a superconducting synchronous machine from the space around it with the aid of a ferromagnetic or superconducting shield.

This article presents results of the investigation of the magnetic field of a superconducting field winding of a machine with ferromagnetic and superconducted shields; the equations obtained are also valid for nonsuperconducting machines of similar construction.

Let us examine a magnetic system with a fixed superconducting field winding located inside the shield (Fig. 1) in a cylindrical coordinate system. We make the following assumptions:

the magnetic field is plane-parallel;

the magnetic permeability of the field winding material is constant and equal to $\mu_0$. When the field winding is powered by a source with an automatic current-control system the superconducting material works with fields close to critical and, besides, when the winding is made of a superconductor stabilized with a normal metal the space factor is equal to, approximately, 0.1:

magnetic permeability of the shield is constant and equal to $\mu_э$

Let us write the following relationships for the vector potential and field strength:

$$\bar{A} = \frac{\mu_0}{4\pi}\int\limits_v \frac{\bar{j}\,dv}{a};$$
$$\bar{H} = \frac{1}{\mu_0}\operatorname{rot}\bar{A}. \tag{1}$$

The method of electromagnetic images is used for solving the problem. The strength of the magnetic field at any point of space included within the shield is determined by the real current of the superconducting field winding and by the fictitious current at distance of $r' = r_0 2/r$ beyond the edge of the shield [2]. The magnitude of the fictitious current is related to the real current by the coefficient

$$k_\mu = \frac{1-\dot{\mu}_0}{1+\dot{\mu}_0},$$

where

$$\dot{\mu}_0 = \frac{\mu_0}{\mu_э}.$$

The components of the magnetic field strength are written in the following form:

$$H_{\rho\Sigma} = H_\rho + H_\rho';$$
$$H_{\varphi\Sigma} = H_\varphi + H_\varphi'. \tag{2}$$

The values of the radial and tangential components of the magnetic field strength, $H_\rho$ and $H_\varphi$, caused by the real current, are found from familiar formulas [1]. The values of $H_\rho'$ and $H_\varphi'$ are defined in terms of the vector potential of the magnetic field:

$$H_\rho' = \frac{1}{\mu_0 \rho} \frac{\partial A'}{\partial \varphi};$$
$$H_\varphi' = -\frac{1}{\mu_0} \frac{\partial A'}{\partial \rho}. \qquad (3)$$

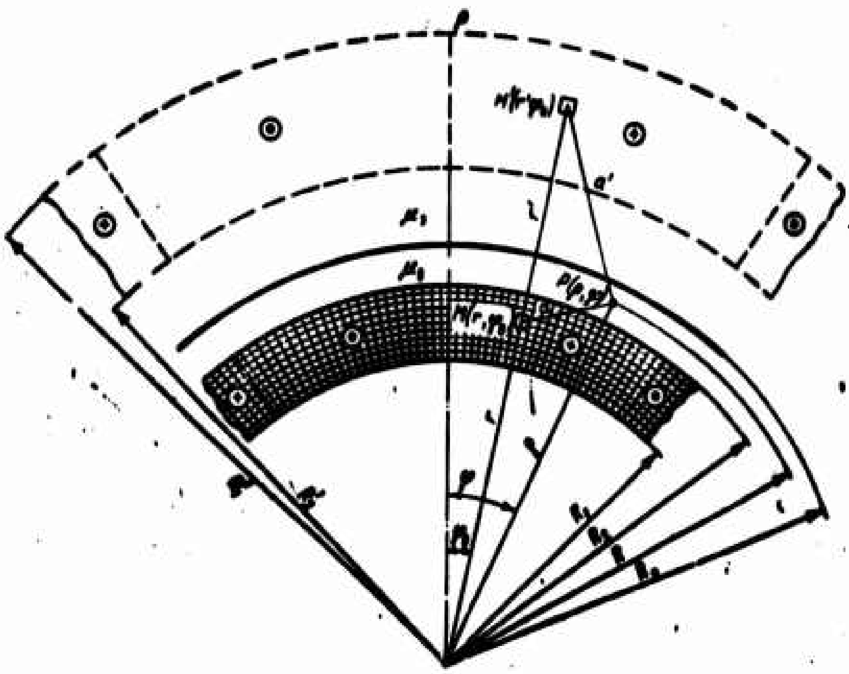

Fig. 1. Field winding of a shielded superconducting synchronous machine.

The axial component of the vector potential function at point P ($\rho$, $\varphi$) is equal to:

$$A' = \frac{\mu_0}{2\pi} \int_{S'} j' r' dr' d\varphi_0 \ln a'. \qquad (4)$$

where S' is the area occupied by conductors with a fictitious current;

$$j' = j_{cp} k_\mu \left(\frac{r_0}{r'}\right)^4;$$
$$a' = \sqrt{\rho^2 + r'^2 - 2\rho r' \cos(\varphi - \varphi_0)};$$

$j$ and $j_{cp}$ are respectively the fictitious and the real current density. Let us write the vector potential in the form of a Fourier series:

$$A' = \frac{\mu_0}{2\pi} \int_{S'} j' r' dr' d\varphi_0 \sum_{n=1}^{\infty} \frac{1}{n} \left(\frac{\rho}{r'}\right)^{np} \cos np(\varphi - \varphi_0). \qquad (5)$$

After integration over every section occupied by conductors with fictitious current, substitution in equations (3), and introduction (for convenience of further calculations and the construction of graphic dependences) of the relative dimensions

$\overset{*}{R}_1 = R_1 / R_2$, $\overset{*}{R} = R / R_2$ and $\overset{*}{R}_0 = R_0 / R_2$,

we get

$$H_\rho' = j_{cp} \frac{R_2}{4\pi} K_\rho' \cos np\varphi;$$

$$H_\varphi' = -j_{cp} \frac{R_2}{4\pi} K_\varphi' \sin np\varphi,$$

where

$$K_\rho' = K_\varphi' = k_\mu \sum_{n=1}^{\infty} \frac{8}{n(np+2)} \frac{1 - \overset{*}{R}_1^{np+2}}{\overset{*}{R}_0^{2np}} \overset{*}{R}^{np-1}. \qquad (6)$$

For a ferromagnetic shield we assume $\mu_3 = \infty$ and $k_\mu = 1$. Then with one member of the series ($n = 1$) expression (6) will have the form:

$$K_{\rho 1}' = \frac{8 \overset{*}{R}^{p-1} \overset{*}{R}_0^{-2p}}{2+p} (1 - \overset{*}{R}_1^{p+2}). \qquad (7)$$

The dependences of $K_{\rho 1}'$ on $\overset{*}{R}$ and $\overset{*}{R}_1$ for $p$ equal to 1, 2, 3 and 4 are illustrated in Figs. 2-5. From the graphs in these figures it follows that the components of the magnetic field strength that are proportional to the coefficient $K_\rho'$ have their greatest value on the inner surface of the ferromagnetic shield and are equal, in absolute magnitude, to the values of the strength at these points in the absence of a ferromagnetic shield. The total radial strength component in this case doubles, while the total tangential component becomes zero.

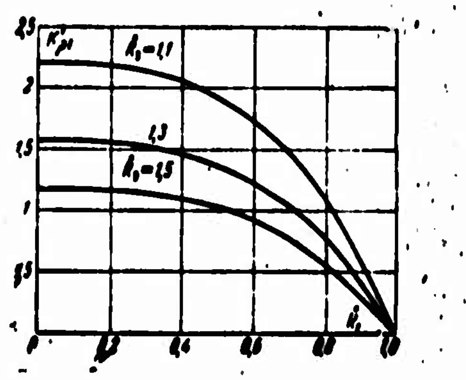

Fig. 2. Dependence of $K_{\rho 1}'$ on j '$R_1$) for p = 1.

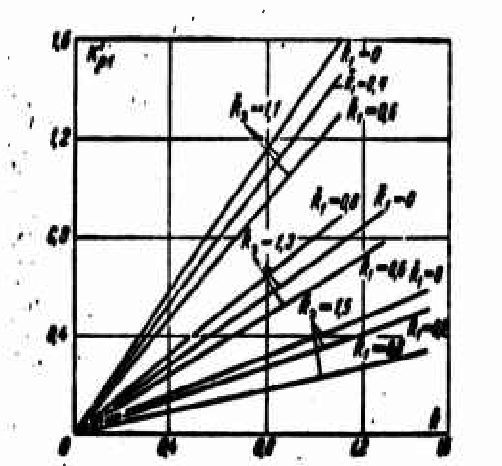

Fig. 3. Dependence $K_{\rho 1}' = f(\overset{*}{R})$ for p = 2.

Distribution of the total radial magnetic field strength component along the radius is shown in Fig. 6.

Thus, an almost two-fold increase in strength in the region occupied by the armature coil leads to the growth of the emf induced in it. For machines with a superconductive shield $k_\mu = -1$. The strength component $H_\rho'$ in relation to $H_\rho$ has a negative sign, with the result that the total radial strength component is less than $H_\rho$, and on the inner surface of the shield it acquires a value of zero (Fig. 7).

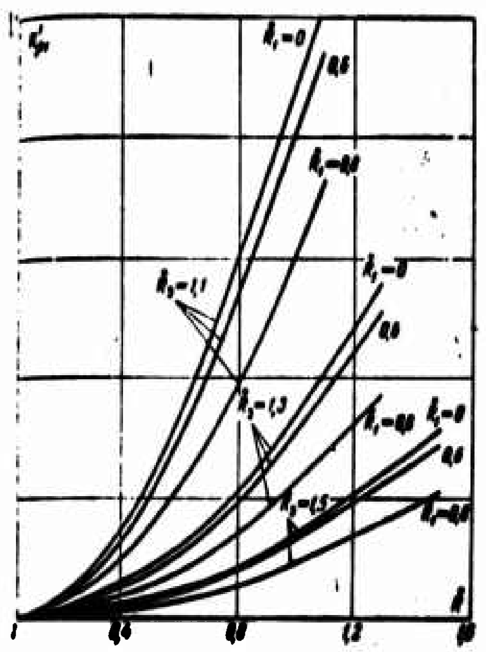

Fig. 4. Dependence $K_{\rho 1}' = f(\overset{*}{R})$ for $p = 3$.

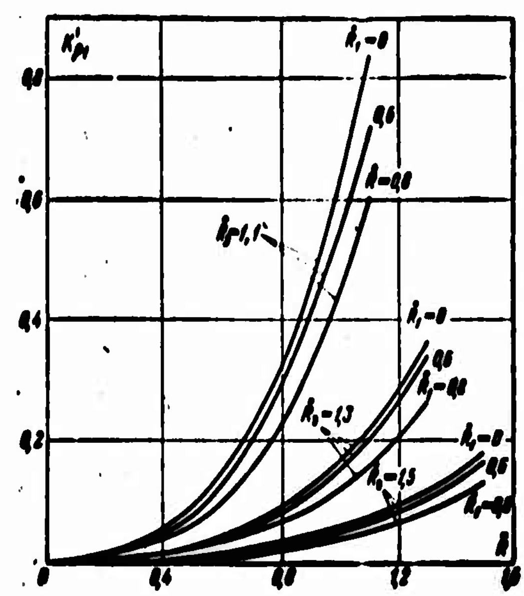

Fig. 5. Dependence $K_{\rho 1}' = f(\overset{*}{R})$ for $p = 4$.

If the machine has a ferromagnetic or a superconducting shield the field shape factor is expressed as follows:

$$k_{1\rho} = \frac{H_{\rho 1\rho}}{H_{\rho\rho}} = \frac{H_{\rho 1} + H_{\rho 1}'}{H_\rho + H_\rho'}. \qquad (8)$$

The above-obtained expression for $H_\rho'$ is presented in the form of an infinite series necessary for defining $H_{\rho 1}'$. The expression for $H_\rho'$ can also be realized in finite form.

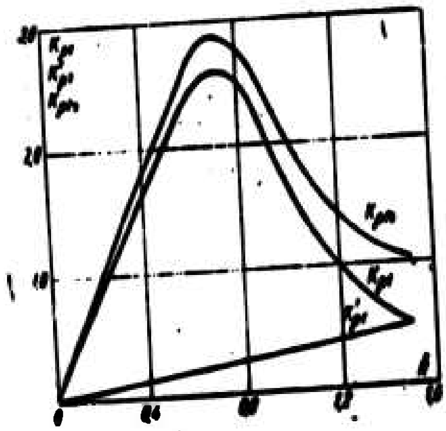

Fig. 6. Dependences of $K_{\rho 1}$, $K_{\rho 1}'$, $K_{\rho 1 э}$ on $\overset{*}{R}$ for $p = 2$, $\overset{*}{R}_э = 1.5$, $\mu_э = \infty$.

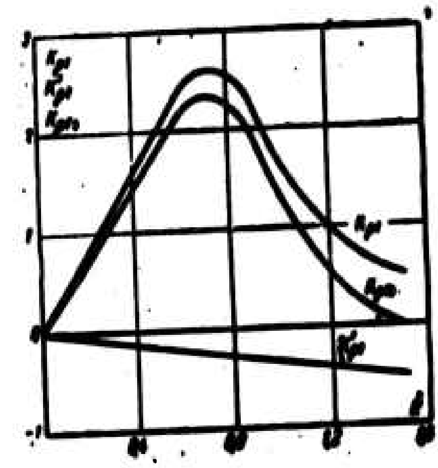

Fig. 7. Dependences of $K_{\rho 1}$, $K_{\rho 1}'$, $K_{\rho 1 э}$ on $\overset{*}{R}$ form $p = 2$, $R_1 = 0.6$, $R_э = 1.5$, $\mu_э = 0$.

Not expanding the vector potential function in a series, we select definite integral (4):

$$\Pi_\rho' = I_{\omega} \frac{R_2}{4\pi} K_\rho',$$

where

$$K_\rho' = \sum_{n=1}^{n=2p} (-1)^{n+1} k_\rho \Bigg[ \frac{1}{2\mathring{R}} \ln \frac{\mathring{R}_0^4 + \mathring{R}^2 - 2\mathring{R}_0^2 \mathring{R}\cos\alpha}{\mathring{R}_0^4 + \mathring{R}^2 - 2\mathring{R}_0^2 \mathring{R}\cos\beta} -$$
$$- \frac{\mathring{R}_1}{2\mathring{R}} \ln \frac{\mathring{R}_0^4 + \mathring{R}^2 \mathring{R}_1^2 - 2\mathring{R}_0^2 \mathring{R}\mathring{R}_1 \cos\alpha}{\mathring{R}_0^4 + \mathring{R}^2 \mathring{R}_1^2 - 2\mathring{R}_0^2 \mathring{R}\mathring{R}_1 \cos\beta} -$$
$$- \left( \frac{\mathring{R}_0^4}{\mathring{R}^2} \cos^2\alpha - \frac{\mathring{R}_0^4}{2\mathring{R}^2} \right) \ln \frac{\mathring{R}_0^4 + \mathring{R}^2 - 2\mathring{R}_0^2 \mathring{R}\cos\alpha}{\mathring{R}_0^4 + \mathring{R}^2 \mathring{R}_1^2 - 2\mathring{R}_0^2 \mathring{R}\mathring{R}_1 \cos\alpha} +$$
$$+ \left( \frac{\mathring{R}_0^4}{\mathring{R}^2} \cos^2\beta - \frac{\mathring{R}_0^4}{2\mathring{R}^2} \right) \ln \frac{\mathring{R}_0^4 + \mathring{R}^2 - 2\mathring{R}_0^2 \mathring{R}\cos\beta}{\mathring{R}_0^4 + \mathring{R}^2 \mathring{R}_1^2 - 2\mathring{R}_0^2 \mathring{R}\mathring{R}_1 \cos\beta} +$$
$$+ \frac{\mathring{R}_0^2}{\mathring{R}^2} (1 - \mathring{R}_1)(\cos\beta - \cos\alpha) +$$
$$+ \frac{\mathring{R}_0^4}{\mathring{R}^2} \sin 2\alpha \left( \operatorname{arctg} \frac{\mathring{R} - \mathring{R}_0^2 \cos\alpha}{\mathring{R}_0^2 \sin\alpha} - \operatorname{arctg} \frac{\mathring{R}\mathring{R}_1 - \mathring{R}_0^2 \cos\alpha}{\mathring{R}_0^2 \sin\alpha} \right) -$$
$$- \frac{\mathring{R}_0^4}{\mathring{R}^2} \sin 2\beta \left( \operatorname{arctg} \frac{\mathring{R} - \mathring{R}_0^2 \cos\beta}{\mathring{R}_0^2 \sin\beta} - \operatorname{arctg} \frac{RR_1 - R_0^2 \cos\beta}{\mathring{R}_0^2 \sin\beta} \right) \Bigg], \qquad (9)$$
$$\alpha = \varphi - \pi\left( \frac{n}{p} - \frac{1-\gamma}{2} \right); \quad \beta = \varphi - \pi\left( \frac{n-1}{p} + \frac{1-\gamma}{2} \right);$$

$\gamma$ – the ratio of the wound part of the pole to the entire polar section.

The maximum value of $K_\rho'$ with $\varphi = 0$, $\gamma = 1$, and $\mu_э = \infty$ for various numbers of pairs of poles equals:

when p = 1

$$K_\rho' = \left(\frac{2}{\mathring{R}} - \frac{2\mathring{R}_0^4}{\mathring{R}^3}\right)\ln\frac{\mathring{R}_0^2+\mathring{R}}{\mathring{R}_0^2-\mathring{R}} - \left(\frac{2\mathring{R}_1^2}{\mathring{R}^3} - \frac{2\mathring{R}_0^4}{\mathring{R}^3}\right)\ln\frac{\mathring{R}_0^2+\mathring{R}\mathring{R}_1}{\mathring{R}_0^2-\mathring{R}\mathring{R}_1} + 4\frac{\mathring{R}_0^2}{\mathring{R}^2}(1-\mathring{R}_1); \tag{10}$$

when p = 2

$$K_\rho' = \frac{2}{\mathring{R}}\ln\frac{\mathring{R}^2+\mathring{R}_0^4}{\mathring{R}^2-\mathring{R}_0^4} - \frac{2\mathring{R}_1^2}{\mathring{R}}\ln\frac{\mathring{R}^2\mathring{R}_1^2+\mathring{R}_0^4}{\mathring{R}^2\mathring{R}_1^2-\mathring{R}_0^4} + \frac{2\mathring{R}_0^4}{\mathring{R}^3}\ln\frac{\mathring{R}^4-\mathring{R}_0^8}{\mathring{R}^4\mathring{R}_1^4-\mathring{R}_0^8}; \tag{11}$$

when p = 3

$$\begin{aligned} K_\rho' ={}& \left(\frac{2}{\mathring{R}} + \frac{\mathring{R}_0^4}{\mathring{R}^3}\right)\ln\frac{\mathring{R}^3+\mathring{R}_0^6}{\mathring{R}^3-\mathring{R}_0^6} - \left(\frac{2\mathring{R}_1^2}{\mathring{R}} + \frac{\mathring{R}_0^4}{\mathring{R}^3}\right)\ln\frac{\mathring{R}^3\mathring{R}_1^3+\mathring{R}_0^6}{\mathring{R}^3\mathring{R}_1^3-\mathring{R}_0^6} + \\ &+ \frac{3\mathring{R}_0^4}{\mathring{R}^3}\ln\frac{\mathring{R}-\mathring{R}_0^2}{\mathring{R}+\mathring{R}_0^2} - \frac{3\mathring{R}_0^4}{\mathring{R}^3}\ln\frac{\mathring{R}\mathring{R}_1-\mathring{R}_0^2}{\mathring{R}\mathring{R}_1+\mathring{R}_0^2} + \frac{2\sqrt{3}\mathring{R}_0^4}{\mathring{R}^3}\left(\operatorname{arctg}\frac{2\mathring{R}+\mathring{R}_0^2}{\sqrt{3}\mathring{R}_0^2} - \right. \\ &\left. - \operatorname{arctg}\frac{2\mathring{R}\mathring{R}_1+\mathring{R}_0^2}{\sqrt{3}\mathring{R}_0^2} + \operatorname{arctg}\frac{2\mathring{R}-\mathring{R}_0^2}{\sqrt{3}\mathring{R}_0^2} - \operatorname{arctg}\frac{2\mathring{R}\mathring{R}_1-\mathring{R}_0^2}{\sqrt{3}\,\mathring{R}}\right); \end{aligned} \tag{12}$$

when p = 4

$$\begin{aligned} K_\rho' ={}& \frac{2}{\mathring{R}}\ln\frac{\mathring{R}^4+\mathring{R}_0^8}{\mathring{R}^4-\mathring{R}_0^8} + \frac{2\mathring{R}_1^2}{\mathring{R}}\ln\frac{\mathring{R}^4\mathring{R}_1^4+\mathring{R}_0^8}{\mathring{R}^4\mathring{R}_1^4-\mathring{R}_0^8} + \\ &+ \frac{2\mathring{R}_0^4}{\mathring{R}^3}\ln\frac{(\mathring{R}^2-\mathring{R}_0^4)(\mathring{R}^2\mathring{R}_1^2+\mathring{R}_0^4)}{(\mathring{R}^2+\mathring{R}_0^4)(\mathring{R}^2\mathring{R}_1^2-\mathring{R}_0^4)} + \frac{4\mathring{R}_0}{\mathring{R}^3}\left(\operatorname{arctg}\frac{\sqrt{2}\mathring{R}-\mathring{R}_0^2}{\mathring{R}_0^2} - \right. \\ &\left. - \operatorname{arctg}\frac{\sqrt{2}\mathring{R}\mathring{R}_1-\mathring{R}_0^2}{\mathring{R}_0^2} - \operatorname{arctg}\frac{\sqrt{2}\mathring{R}+\mathring{R}_0^2}{\mathring{R}_0^2} + \operatorname{arctg}\frac{\sqrt{2}\mathring{R}\mathring{R}_1+\mathring{R}_0^2}{\mathring{R}_0^2}\right). \end{aligned} \tag{13}$$

The field shape factor when $\mu_{\text{э}} = \infty$ and $k_{\mu} = 1$ equals

$$k_{f\text{э}} = \frac{K_{\rho 1} + K_{\rho 1}'}{K_{\rho} + K_{\rho}'}.$$

In the case when $\mu_{\text{э}} = 0$ and $k_{\mu} = -1$,

$$k_{f\text{э}} = \frac{K_{\rho 1} - K_{\rho 1}'}{K_{\rho} - K_{\rho}'}.$$

The dependence $k_{f\text{э}} = f(\overset{*}{R})$ when p = 2 is depicted in Fig. 8.

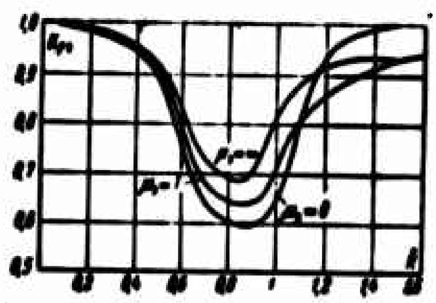

Fig. 8. Dependence $K_{f\text{э}} = f(\overset{*}{R})$ for $p = 2$, $R_1 = 0.6$, $\overset{*}{R}_{\text{э}} = 1.5$.

The field shape factor inside the area limited by the shield has, when $\mu_{\text{э}} = \infty$, smaller values in comparison with machines without a shield. On the surface of the shield the field shape factor when $\mu_{\text{э}} = 0$ becomes equal to one, while when $\mu_{\text{э}} = \infty$ it remains without change, just as when $\mu_{\text{э}} = 1$.

## Conclusions

Analysis of the obtained expressions for the components of the magnetic field strength for superconducting synchronous machines with a ferromagnetic shield shows that the magnetic strength inside the shield increases.

The presence of a superconducting shield adversely affects the distribution of the resultant radial magnetic field strength component; such a shield is used expediently with external magnetic fields of dispersion which exceed the saturation limits of the ferromagnetic material.

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ABSTRACT

(U) The magnetic field of the superconducting winding of a shielded synchronous machine is investigated, expressions for components of magnetic field strength are obtained, and the shape factor of the field of a synchronous machine with ferromagnetic and superconducting shields is determined. Graphic dependences are given for the distribution of the components of magnetic field strength along the radius for various numbers of pairs of poles, and the relationship of geometrical dimensions of a superconducting winding and shield is shown.